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Human Settlements in a Changing Climate: Impacts and Adaptation

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EXECUTIVE SUMMARY

Climate change will occur against a background of other non-climate environmental factors and socioeconomic factors that could either exacerbate or mitigate the effects of climate change. These other factors may, in many cases, dominate climate change. As compared with the 1990 or 1992 IPCC assessments of impacts, this discussion emphasizes the multiple and interactive pathways by which climate change exacerbates or mitigates the effects of other events that nations may find important. These interactions could occur in unexpected ways, with small changes having disproportionately large outcomes. The major conclusions follow.

Impacts on human settlements from climate change may be indirect, as well as direct. Direct effects of sea-level rise and extreme events are known to be important in coastal zones and island nations. However, many of the impacts on human settlements from climate change are likely to be experienced indirectly through effects on other sectors (for example, changes in water supply, agricultural productivity, and human migration). We have high confidence in the importance of these indirect effects because they depend on well-known mechanisms of social interaction rather than data specific to the climate of the future.

Thresholds beyond which impacts escalate quickly are unique to individual local situations and tend to depend on the degree of adaptive response. For example, the impact of sea-level rise on coastal communities critically depends on the degree to which human lives and assets can be protected, insured, or shifted to new locations that are unthreatened. As discussed in 1990 and 1992, the human settlements most vulnerable to climate change are likely to be in locations already stressed by high rates of population growth, urbanization, and environmental degradation. However, in addition to islands, coastal communities, and communities dependent on marginal rain-fed agriculture or commercial fishing discussed in the previous reports, vulnerable settlements include large primary coastal cities and especially squatter settlements located in flood plains and on steep hillsides. We have medium confidence in this result. The consensus is strong concerning the principle, but the data supporting it apply mainly to analogous circumstances.

Non-climate effects may be more important than climate change. Local environmental and socioeconomic situations are changing rapidly for reasons other than climate change. Worldwide, population growth, industrialization, urbanization, poverty, technological change, and government policy could overwhelm any effects of climate change. We have low confidence in this finding because the result is a matter of some controversy and there is insufficient data on climate-change effects on human settlements relative to those of other disturbances to resolve it.

A significant potential for noncoastal flooding (river basin and local urban flooding) is expected if precipitation intensity increases as a result of climate change. The IPCC Working Group I volume (Chapter 6, *Climate Models–Projections of Future Climate*) states that precipitation intensity may increase and that several models now project increases in higher-rainfall events. If intensity increases, the risk of flooding to settlement infrastructure could be very widely distributed across the planet, not just in coastal zones. One particular problem in providing estimates of damage is specifying the extent of future human intrusion into disaster-prone areas. We have low confidence in this finding because the consensus of climate modelers concerning the effects of climate change on intense rainfall events does not extend to regions and localities and because the degree of adaptation is likely to be important.

Health risks are potentially very large, especially in the informal settlements on the fringes of megacities of the developing world, but the probabilities are difficult to estimate. Current patterns of urbanization, extended into the next century, suggest that the most vulnerable human populations may become even more vulnerable. Economic and environmental refugees may introduce a number of exotic diseases into temperate-zone human settlements. Increased climate variability and associated extreme events can add new breeding sites and new bursts of activity for vector-borne diseases. This finding relies on the best thinking of the community of epidemiologists, but our confidence in the finding varies with the particular disease and location and because necessary supporting environmental data are adequate in some cases and extremely sketchy in others (see also Chapter 18).

Some other important findings are as follows:

- **Migration**—Many of the expected impacts in the developing world will occur because climate change may, by reducing natural resource productivity in rural areas, accelerate rural-to-urban migration, exacerbating already crowded conditions in the cities and further depleting the labor force of the countryside.
- **Water and Biomass**—Global warming can be expected to affect the availability of water resources and biomass, both of which are major energy sources

in many developing countries. Water and biomass resources are already under stress in many of these areas as a result of rising demand. Loss of water and biomass resources may jeopardize energy supply and materials essential for human habitation and energy production.

- **Energy**—Increasing human population and wealth provide a rising energy-demand baseline against which the consequences of changing climate will be played out. Energy demand will be affected by warming, but the direction and strength of the impact will depend on the extent of demands for space heating or cooling and the role of climate-sensitive sources of demand, such as irrigation pumping. Many of the largest increases in baseline demand will occur in developing countries, although not necessarily the largest changes as a result of climate.
- **Adaptation**—Many adaptive mechanisms are available to address each of the potential direct and indirect impacts of climate change on human settlements. The cost and effectiveness of each depend upon local circumstances.

12.1. Introduction

12.1.1. Why Human Settlements

A potentially important way in which climate change could affect human beings is through its effects on human settlements. Settlements, especially cities, have a central role in civilization as the primary generators of human wealth and the engines of social interaction and change. Whether explicitly acknowledged or not, environmentally appropriate economic and social development in settlements is a major goal of national environmental policy throughout the world. According to the United Nations Centre for Human Settlements, a human settlement can be judged on four criteria: (1) the quality of life it offers to its inhabitants; (2) the scale of nonrenewable resource use (including reuse); (3) the scale and nature of the use of renewable resources and the implications of the settlement's demands for sustaining production levels of these resources; and (4) the scale and nature of nonreusable wastes generated by production and consumption activities, the means by which these are disposed of, and the extent to which wastes affect human health, natural systems, and amenity values (Habitat, 1992a). Climate change could affect the sustainability of human settlements either by directly affecting the quality of life in settlements (e.g., by changing the probability of floods or the effects of air-pollution episodes), by modifying the effects of the settlements on their surrounding environments (e.g., by changing the demand for water or changing the assimilation capacity of wetlands), or by changing the economic underpinnings of the settlement (e.g., by changing the productivity of croplands, forests, or fisheries on which the settlement depends).

The 1990 and 1992 IPCC assessments dealt only with the direct effects of climate on human settlements, primarily infrastructure issues. The more subtle effects of human-settlement metabolism may be more important in some instances. Moreover, consideration of the indirect effects of climate change shifts the focus of attention from a narrow and necessarily speculative concern over future impacts on infrastructure to the more general pressing problems of economic and social development. Included in development could be an adaptation policy that includes a variety of adaptive mechanisms.

12.1.2. Guide to the Chapter

This chapter begins with a discussion of the non-climate environmental and socioeconomic factors that are expected to interact with climate change and sea-level rise (see Figure 12-1) in producing effects on human settlements. Some of the non-climate effects (e.g., urbanization or pollution) are likely to be significant enough in many cases to dominate the effects of climate alone but in any case could exacerbate climate effects. The chapter then discusses the possible impacts of climate on various sectors that might be affected (e.g., population, energy demand and supply, infrastructure, and water supplies). Some of these sectors have chapters of their own; however, this chapter emphasizes not only the direct effects of climate on human settlements but also the relationships between human settlements and these other, more directly affected, sectors. Finally, this chapter discusses adaptive responses to climate change—both those that may be taken autonomously by human settlements in response to climate change and other stresses and those that may be undertaken as a matter of deliberate adaptive policy by governments. Some readers will be disappointed that the chapter contains very few quantitative estimates of impact. This is by design. The very variety of human settlements and complexity of their environmental circumstances assure that almost any impact estimates will be local in scope and that both the absolute and relative importance of the various effects will be different in almost every circumstance. Except for sea-level rise, where some international estimates exist, the few estimates in the literature of the impact of climate change on human-settlement infrastructure and inhabitants are local and regional in scope. No study has yet attempted the difficult aggregation of climate and non-climate effects required for a proper analysis. Thus, the quantitative estimates provided in the chapter should be regarded as illustrative and anecdotal in nature.

12.2. Non-Climate Factors

A major difficulty in determining the impact of climate change on human habitat is the fact that many other factors, largely independent of climate change, are also important. In many cases, these other factors are far more important than climate change in terms of the risk they pose for human settlements. These non-climate factors will also increase the vulnerability of some regions to climate change. The most important of these factors include population growth, urbanization and industrialization, technology choices, and government policies. Other social factors, such as cultural clashes and warfare, also play a role. Vulnerability of settlements has to be judged on the basis of the susceptibility of the settlement's resources to damage via climate change, conditioned by the resilience of the resources and the technical, institutional, economic, and cultural capabilities of the settlement to cope with or manage the change

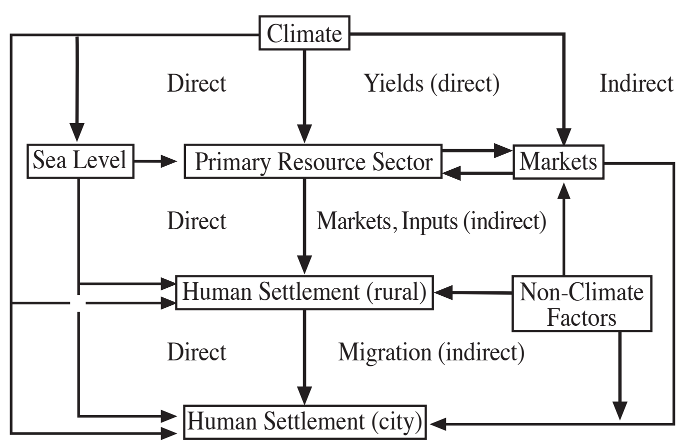

Figure 12-1: Relationship between direct and indirect effects of climate change, sea-level change, and non-climate factors on resource sectors, rural human settlements, and cities.

(IPCC CZMS, 1992; Turner *et al*., 1994). One can reliably predict that certain developing countries will be extremely vulnerable to climate changes because they are both susceptible to the change and already at the limits of their capacity to cope with climatic events. These include populations in low-lying coastal regions and islands, subsistence farmers, populations in semiarid grasslands, and the urban poor.

12.2.1. Economic and Social Development

12.2.1.1. Population Growth

The population of the world is estimated at about 5.3 billion. At its peak in the late 1960s and early 1970s, the average annual rate of increase in the world's population was close to 2%. Projections suggest that this rate of increase will fall to less than 1% by the second decade of the 21st century. However, the rate of abatement in the growth rate is expected to vary sharply from region to region. For example, whereas the world's population as a whole is expected to grow at 1.3% per year on average between 2000 and 2025, population is expected to grow at 2.1% in low-income countries but at only 0.2% in the Organization for Economic Cooperation and Development (OECD) countries (World Bank, 1991). Further, the differences in birth rates between rural and urban areas have widened, according to the United Nations World Fertility Survey (1986). Regions already struggling to cope with exploding populations can be expected to be exceptionally vulnerable to climate change.

12.2.1.2. Industrialization and Urban Growth

Since 1950, the number of people living in cities has tripled, increasing by more than 1.25 billion (World Commission on Environment and Development, 1987). By 1980, nearly one in three persons was an urban dweller, and one in ten lived in a city with a million or more inhabitants (a "million city"). By 1990, an estimated 42.65% of the world's people were urban residents. It has been estimated that by 2025 60% of the world's people will be living in towns and cities. In many countries, the fastest-growing areas are in coastal regions and estuaries, many of which are vulnerable to extreme events and sea-level rise (Marco and Cayuela, 1992). Already, two-thirds of the world population lives within 60 km of the coast; this is expected to rise to 75% by the year 2010 (WCC'93, 1994). The developed world has heavily concentrated its people in coastal areas (Friedman, 1984; Handmer, 1989; Marco, 1992; Boissonade and Davy, 1993; Lester, 1993; Skinner *et al*., 1993; WCC'93, 1994).

Urbanization has been growing much faster and creating higher urban densities in developing countries than in developed countries (Berry, 1990). Although significant differences exist between countries, in developing countries as a group the urban population is growing much faster than in the industrialized countries. In the developing countries, the urban population is growing by an average of 3.6% per year compared to only 0.8% in the industrialized countries, which are believed to have essentially completed their urbanization process and in some cases are de-urbanizing. The uncontrolled expansion of towns and cities in the developing countries has led to overwhelmed transport, communications, water-supply, sanitation, and energy systems. Urban sprawl preempts other land uses near these towns and cities. Between 1980 and 2000, urban areas in developing countries are expected to grow from about 8 million hectares to more than 17 million hectares. The development policy in most developing countries after World War II favored modernization biased toward the urban-industrial sector, especially manufacturing targeted to satisfy domestic demand. In Latin America, for example, "import-substitution industrialization" registered an unprecedented success between 1950 and 1970; the regional gross domestic product (GDP) grew at an annual average rate of 5%. However, rural public investment was neglected, and the rural labor force was economically marginalized. Excess rural labor migrated to urban unemployment and informal activities (PNUMA/MOPU/AECI, 1989, Part III). Some analyses emphasize the attraction of cities ("pull factor") in the rural exodus, while others point out the aggravation of high rural population growth and the expelling process in rural areas ("push factor"). The latter definitely played a fundamental role in migration. In the last decades, rural life conditions have experienced continuous deterioration in relative and absolute terms, and large sectors of peasants have been excluded from the modernization process (Armstrong and McGee, 1985, Chapters 4 and 5), leaving them more vulnerable to climate variability. Growing scales of urban metabolism (urban demands for natural resources and the increase in the inflow and outflow of materials, products, energy, water, people, and wastes) add to pressures on the environment and could exacerbate the effects of climate change. Particularly salient has been the rapid growth of motorized transportation in urban areas.

12.2.1.3. Poverty

In the 1980s, many developing countries not only failed to keep pace with the industrial countries but saw their incomes fall. The living standards of millions in Latin America are now lower than in the early 1970s; in most of sub-Saharan Africa, living standards have fallen to levels last seen in the 1960s. According to some estimates, the percentage of the world's population living in absolute poverty decreased, at least up to the middle of the 1980s, but the absolute number of poor has increased (United Nations, 1989; Gilbert, 1992). It was estimated that in 1985 1.115 billion people lived in poverty in the developing world. That is approximately one-third of the total population of the developing world. Of these, 630 million were extremely poor (World Bank, 1990). Nearly half of the developing world's poor, and nearly half of those in extreme poverty, live in South Asia, followed in order by sub-Saharan Africa, the Middle East and North Africa, Latin America, the Caribbean, and East Asia (World Bank, 1990). What is particularly relevant for environmental management purposes is that poverty has "urbanized": The number of poor in the world increased 11% from 1970 to

1985, but the number of urban poor expanded 73% worldwide and up to 81% in Africa. Poverty compounds the effects of inadequate drinking water, poor sanitation, and housing in crowded buildings constructed in flood-prone areas and other dangerous circumstances (Habitat, 1992b). In addition, it restricts the ability of communities to invest in practices and technologies that may be more environmentally appropriate. In some cases, poverty restricts access to education and information about better practices that are available. Although extremely serious in themselves, all of these factors are likely to compound any negative impacts of climate change.

12.2.2. Technology

12.2.2.1. Infrastructure

The choices that people make concerning which technology is used to provide a given service may have a dramatic impact on the degree to which a given change in climate will affect human settlements. For example, periodic additions of mechanization in North American agriculture during the last century (e.g, tractors, self-propelled harvesters, center-pivot irrigation) have significantly reduced the number of people engaged in agriculture and the accompanying requirements for their economic and social support services. As a consequence, there are now fewer settlements dependent on agriculture or likely to be directly affected by drought, flood, or other weather incidents. Previous choices of technology may also considerably restrict the options available for adaptation. For example, the ordinary operating life of commercial buildings in the United States is about 80 to 90 years (Pierce, 1994), whereas the life of water-supply systems is around 50 years (Internal Revenue Service, 1994). It follows that climate changes occurring in the first half of the 21st century would affect energy and water-supply systems that will mostly look like today's. The viability of entire transportation systems—for example, the bias that exists toward automobiles in many human settlements throughout the world—is influenced strongly by past technological choices and spatial patterns of settlement that grew up around these choices. This, in turn, has significantly influenced the long-term livability and viability of these settlements.

Standard engineering practice calls for safety standards of drains, culverts, bridges, dikes, and dams. Based on historical data, these are built to withstand 25-year, 50-year, 100-year, or 400-year floods. If rainfall intensity increases with climate change (Pittock, 1994), these structures either would have to be built to a higher standard or a greater probability of damage accepted. A structure strong enough to withstand a 25-year flood in the future might have to be strong enough to withstand a flood now considered to be a 100-year event. Today's structures would have a higher risk of failure. Lowering this risk would require investments that compete for very limited discretionary dollars, especially in many developing countries.

There is a huge unsatisfied demand for shelter in developing countries. Indeed, construction of living space is among the more energy-intensive activities in some countries, contributing 17% of India's annual carbon dioxide emissions, for example (Tiwari and Parikh, 1993). In addition, in developed countries, existing buildings contribute a large portion of the primary fuel use and greenhouse gas (GHG) emissions. In the United Kingdom and Western Europe, the percentage may be some 50% (Courtenay, 1992). If mitigation of climate change requires large increases in energy costs, the impacts on this sector and on human settlements could be significant.

12.2.2.2. Environmental Management

The manner in which human settlements dispose of their waste, and even the degree to which they declare certain physical outputs of production and consumption processes to be "waste," reflects a series of social choices. The consequences of those choices on the environment varies widely and may be affected by climate change.

For example, the most common method for disposing of solid waste is land disposal, either sanitary landfill or simply disposing of the waste on unused land. Leakage and runoff from landfills and wastes released to surface waters adversely affect the quality of ground and surface waters. In some cases, an incinerator is used to reduce the volume of the organic component (Habitat, 1992a). To reduce the burden on landfills, resource recovery by one of several strategies can be pursued and may be more likely in less-wealthy settlements (Habitat, 1992a). However, if settlements are poor, less-safe technologies may be used for disposal. If climate changes, the assimilative capacity of airsheds may be reduced because of increased prevalence of stagnant-air episodes, while sea-level rise and potential flooding could restrict the availability of land for safe disposal of solid waste. At the same time, demand for disposal areas continues to rise.

12.2.3. Policy

12.2.3.1. Land and Development Policies

The rights and conditions under which land is held (land-tenure systems) can strongly affect the management of this resource and either promote or discourage adaptation to environmental conditions of all kinds. Settlement history has a great deal to say about this, and land-tenure systems can result in mismatches between population and productive land. Some traditional land-tenure systems have adapted to unique climate or cultural systems and have significant survival value (Oguntoyinbo, 1991). For example, in some West African land-tenure systems, tenure goes with the crop, not the land. This system encouraged the growing of perennial crops, such as trees. Subsequent conversion to a fee simple absolute system (ordinary private ownership) encouraged the planting of commercial row crops, the opposite of the intended result (Rayner and Richards, 1994). Communally managed commercial livestock-grazing schemes appear to have worked better in Africa than fenced-ranching schemes, in that they permit freer adjustment to spatial variability in rainfall (Thompson and Wilson, 1994). In Mexico, *ejido* usufruct land-tenure systems (now undergoing privatization) have been used, in part, to combat the consequences of variability in rainfall (Thompson and Wilson, 1994) but have been more vulnerable to routine drought and generally show chronic low yields in comparison with private lands that are generally in more favorable locations and can attract higher investments in seed, fertilizer, and water supply (Liverman, 1992). This situation has encouraged rural-to-urban migration. In Nepal, forests were historically managed locally by the community. When the state forest-management system was established, both land tenure and management passed to Kathmandu, and deforestation resulted. A mixed system of state ownership and local control seems to have improved forest management (Thompson, Warburton, and Hatley, 1986). In all cases, local knowledge has proved important.

Some land uses can themselves increase flood hazard by lowering the ground level through drainage (Tooley, 1992) and water extraction (Hadfield, 1994). Deforestation exacerbates runoff, and dams prevent the accumulation of silt on river deltas (Clark, 1991; Kreimer and Munasinghe, 1991). Local flooding can be made worse if much of the settlement's surface area is paved (Berry, 1990; Henri, 1991; Marco and Cayuela, 1992), even in years of great drought (Handmer, 1989).

Government actions (such as zoning practices in flood plains to limit settlement) can reduce adverse interactions between development and climate. However, governments may lack the governance capacity or will to adequately regulate land uses and respond to hazards (Beatley, 1994) or may face sometimes-irreconcilable duties to make settlements both affordable and safe. This quandary manifests itself in floodplains in the conflict over making flood insurance affordable and available without, at the same time, encouraging settlement in areas that have to be defended at great cost (Arnell, 1983; Henri, 1991; Murray, 1991; Denlea, 1994). In addition, government infrastructure investments and other actions can themselves create unfavorable environmental outcomes. In Mexico, Australia, and India, for example, government investment in irrigation has sometimes resulted in high soil salinity and difficulties for the farm communities (Liverman, 1992; Leichenko and Westcoat, 1993). Water-management projects established to cope with frequent drought or flooding have also created poorly assimilated refugee populations. For example, the creation of Lake Kariba, between Zambia and Zaire, has marginalized the Tonga people (Magadza, 1991). Numerous other examples are cited by Gleick (1992). Many of the adverse environmental consequences of urban slums occur because residents lack clear legal tenure and because of the lack of land-use controls.

Most fundamental environmental problems of settlements themselves cannot be tackled unless city governments have the capacity (power, resources, and technical expertise) to intervene in the urban land market. While land-use planning and controls can be problematic everywhere, in many developing countries in particular this lack of capacity, lack of land-use controls, and lack of legal alternatives to unauthorized settlements creates a haphazard, sprawling pattern and density of development that will not allow cost-effective infrastructure and service provision. It also promotes illegal housing on dangerous land sites, sprawl over prime agricultural land, and degradation of the natural landscape (Hardoy and Satterthwaite, 1984; Gilbert, 1992). Even when planning norms exist, they may be weak or unconnected with the way in which land is actually appropriated. In some big urban settlements like Mexico City, planning did not have stipulations to regulate the land market, nor was it associated with concrete programs for addressing priority needs and problems, such as housing and services (Aguilar, 1987; Aguilar and Olivera, 1991).

12.2.3.2. Migrant and Refugee Populations

Conflict between groups in society can exacerbate the effects of climate, creating refugee problems of major dimensions. Such conflict has occurred on the Horn of Africa for 20 years, where successive civil wars in Ethiopia, Eritrea, Somalia, and Sudan have repeatedly disrupted both agriculture and food-delivery systems. Human settlements in many rural areas have been abandoned, and thousands have succumbed to famine and disease (Tolba *et al*., 1992). Adverse climate conditions may compound the plight of refugees (Newland, 1994).

As land and water resources bear increased population and development burdens, disputes over resource use become increasingly acute and may themselves become a source of conflict. For example, in northwest Mexico, the water rights in the Cucurpe area have sometimes become a cause for violence (Liverman, 1992). In the Middle East, Jordan, Israel, and Syria have had great difficulty resolving issues over the distribution of both groundwater and surface waters of the Jordan River Valley (Lowi, 1992; Suhrke, 1993), which contributes to the political instability of that region. Environmental degradation has been a major source of internal social and economic conflict and migration within China (Smil, 1992). Similar (though less extreme) difficulties have attended the distribution of Colorado River water in North America (Glantz, 1988) and Euphrates River water among Turkey, Syria, and Iraq (Gleick, 1992).

In some cases, climate-related environmental disaster has created significant refugee populations, while in other cases the management of resources to prevent disaster has created the problem. These refugee populations are often either socially marginalized or become a source of conflict (Suhrke, 1993). For example, repeated flooding in Bangladesh has resulted in migration of thousands of Bangladeshis to India, where ethnic conflict has resulted (Homer-Dixon *et al*., 1993; Hazarika, 1993).

12.3. Impacts and Ranges of Sensitivities to Climate Change

12.3.1. Population Migration

If future climates resemble those projected by the general circulation models, wetter coasts, drier mid-continent areas, and sea-level rise may cause the gravest effects of climate change through sudden human migration, as millions are displaced by shoreline erosions, river and coastal flooding, or severe drought (e.g., Xia Guang, 1991). In the developing world, many areas to which people might relocate are likely to have insufficient support services to accommodate the new arrivals. Other consequences can include ethnic tensions and regional overpopulation.

Less dramatically, long-term problems with land fertility arising from the interaction between climate and social and agricultural practices produce rural–rural and rural–urban migration. It is known, for example, that a large number of the rural–rural migrants in Nigeria originate in the very densely populated areas where soils are impoverished and have also been destroyed by erosion (Udo *et al*., 1990). Other things being equal, more-intense rainfall accompanying climate change could accelerate these soil-erosion and leaching processes.

Where social safety nets do not intervene and where land uses and techniques are inappropriate, mid-continental droughts have contributed to similar migrations in developed countries (Riebsame, 1990).

In much of the developing world, perhaps 90% of the migrants do not have the special skills that would attract a salary high enough to enable them to live in a better-designed and built urban settlement. Consequently, they end up living in informal peri-urban settlements with some serious infrastructure problems, ranging from unhealthy environment and water supply to difficult access to energy, transportation, communications, and shelter. About one-third of the population in many developing-world cities lives in these informal settlements. Some can be enormous. Ciudad Netzahualcoyotl, the large informal settlement of the 1970s (now a more regular, permanent city) in the Valley of Mexico had more than 1.2 million inhabitants in 1990, according to the Population Census. A newer informal settlement that mainly developed during the 1980s is Valle de Chalco, with an approximate population at the beginning of the 1990s of 400,000 inhabitants (Aguilar and Olivera, 1991; Hiernaux, 1991).

12.3.2. Energy

Generally, studies have shown differing location-specific overall aggregate energy impacts, depending on how much energy use is related to residential and office heating and cooling. Climate warming will increase energy consumption for air conditioning and, conversely, lower it for heating. This result was discussed in the 1990 and 1992 assessments for developed countries. This section confirms those earlier findings and adds some insights on the developing and newly industrialized countries. Because agriculture, transportation, and industry all have been allocated their own sections in this report and because Chapter 22 provides considerable background on fuel use in residential and commercial buildings, this section primarily focuses on energy demand in the residential and commercial sectors as influenced by climate change. Change can be expected in climate-sensitive sources of energy such as hydroelectric power, biomass, solar, and wind. Those resources are discussed in much greater detail in Chapter 11.

12.3.2.1. Demand

Space conditioning of buildings is one of the most climate-sensitive uses of energy—especially the use of electricity for residential and commercial air conditioning, and electricity plus other fuels for space heating. Although usually smaller in total magnitude of energy demand, the use of electricity and fuels for irrigation pumping and the use of fuels for drying of agricultural crops also can be significant weather-sensitive demands in some regions (Scott *et al*., 1993; Darmstadter, 1993). Climate change has negligible direct effect on vehicle performance, but transportation activities are sensitive to immediate impacts from weather and may be indirectly sensitive to gradual shifts in human activities as they respond to climate change and to greenhouse and environmental strategies. For example, if warming should accelerate urbanization tendencies caused by adverse effects on the rural resource base, additional urban congestion could reduce vehicle performance in cities. This performance decline provides incentives for transportation modal shifts (to public transit, for example).

Changes in population, wealth and activities of the population, energy prices, cost and characteristics of technologies used, and daily and seasonal operational patterns for these technologies help drive urban energy demand. For example, discrete zoning of residential and commercial areas may cause higher levels of transportation use (Matsuoka *et al*., 1992). D.W. Jones (1991) found that urbanization was an important determinant of energy demand, though less important than per capita income and industrialization. Mechanization of food delivery and journey to work are major factors. Because the effects of climate change appear to be small in comparison with potential changes caused by these other factors, adjustments can be made to accommodate climate change at small to moderate cost (Linder and Inglis, 1989). A special consideration in considering the effects of urbanization on energy use is the urban "heat island" effect, in which the replacement of vegetative ground cover in urban settlements with structures, streets, and similar surfaces causes outdoor temperatures within these settlements to be several degrees higher than they otherwise would be (Boodhoo, 1991). Energy consumed for air conditioning may increase heat-island effects (Hanaki, 1993). Heat-island effects and actions to reduce them are further discussed in Chapter 22 in the context of the extra energy that must be expended in buildings to counteract heat-island effects.

The sensitivity of space-heating and air-conditioning demand to climate may be estimated in two ways: (1) by using statistical relationships between demand and climate variables of the type routinely used by energy suppliers in carrying out short-run demand forecasting (an analog approach) and (2) by using underlying physical parameters, such as heating or cooling degree-days, to make estimates based on the physical characteristics of buildings (UK Climate Change Impacts Review Group, 1991). In general, the analogue approach results in a lower estimate of climate sensitivity because it takes account of the fact that building occupants may, through autonomous adaptation, adjust their comfort levels. On the other hand, the analogue approach does not take account of some forms of long-term adaptation, notably the modification of building design and space-heating or air-conditioning systems to take account of changed climate conditions (UK Climate Change Impacts Review Group, 1991). In temperate-zone developed countries, investigators have observed that the net balance of energy demand depends largely on the balance between cooling and heating in the residential and commercial sectors (Linder *et al*., 1987; Scott *et al*., 1993; Rosenthal, Gruenspecht, and Mann, 1995). In the commercial sector, air conditioning accounts for a greater proportion of final energy demand, partly because of internal heat gains from lighting, office equipment, and occupants. Generally, in cool areas with limited air conditioning, space-heating fuel use and electricity demand for heating (and, sometimes, total electricity demand) would likely decline (Stokoe *et al*., 1987; Singh, 1988; Mundy, 1990; Aittoniemi, 1991a, 1991b; UK Climate Change Impacts Review Group, 1991; Scott *et al*., 1993). Where cooling is already more important than heating or may become more important, the increase in cooling demand will be greater than the decrease in heating demand (Loveland and Brown, 1990).

In developed countries, increases in commercial building space, space conditioning, and office automation drive much of the overall increase in energy demand and an increase in electricity's share (Nishinomiya and Kato, 1989; Herring *et al*., 1988), while energy-efficiency codes and varieties of green labeling have reduced energy demand. In some cases, climate warming can be expected to further increase both peak and total annual electric power consumption (Linder *et al*., 1987; Linder and Inglis, 1989; Niemeyer *et al*., 1991; Nishinomiya and Nishimura, 1993). However, primary energy demand can still either fall (Nishinomiya and Nishimura, 1993) or rise (UK Climate Change Impacts Review Group, 1991), depending on local conditions.

The relationship between cooling energy and temperature appears to be nonlinear because of latent heat of water condensed by active system cooling equipment and lost efficiency of passive and natural ventilation at high temperatures (Millbank, 1989; Hulme, Haves, and Boardman, 1992; Scott, Hadley, and Wrench, 1994). Huang *et al*. (1987) showed better cooling correlations using degree-hours, latent enthalpy hours, latent cooling loads, and adjustments for natural ventilation. In more recent unpublished work, Huang has shown that a uniform 1.7°C increase in temperature causes about a 12% to 20% increase in cooling loads in cities in newly industrialized or developing countries with hot climates. In cities with cooler climates (e.g., Mexico City, Sao Paulo, Beijing), the estimated increases in cooling loads are larger in relative terms but smaller in absolute terms. Cities in warmer climates may experience large relative decreases in their very small heating loads of 50% or more, virtually eliminating the requirement to heat.

Research in developing countries has shown that appliance use in general (OTA, 1991; Figueroa, Ketoff, and Masera, 1992) and air-conditioning saturation in particular depend on urbanization and income levels. Meyers *et al*. (1990) credited the rapid growth in residential energy use in developing and newly industrialized countries to an increase in the number of households and electrification. Market penetration of air conditioners is still low in most countries, but once they become affordable their proliferation can be very rapid, particularly in hot climates. This has happened in the Philippines, Malaysia, Thailand, Taiwan, and Brazil, which also have humid climates (Schipper and Meyers, 1992). In Taiwan, air-conditioner market penetration more than doubled (12% to 29%) between 1979 and 1989, while in Korea, which has a relatively short summer, it grew from zero in 1976 to 9% in 1989. In comparison, the market penetration of air conditioning in Japan is close to 60%. Similar findings are reported by Sathaye and Tyler (1991) and Parker (1991). Urbanization, rising incomes, and warmer climates could combine to increase both air-conditioner market penetration and cost per unit.

12.3.2.2. Supply

Understanding the effects of climate on hydroelectric, biomass, solar, and wind energy is particularly important because renewable energy sources are playing a significant role in the energy planning of many countries. This could become an increasingly important concern in developing countries, many of which are facing serious economic pressures from the need to import conventional energy resources.

Although cooking usually is a more important end use than heating, woodfuels are particularly important in developing countries because of their (typically) low cost and the simplicity and low cost of the end-use technology (Hall *et al*., 1993). Among the largest potential impacts of climate change on the developing world are the threats in many areas to fuelwood and charcoal, which are principal sources of energy in most sub-Saharan African nations and many other developing countries. For example, cities and towns place large demands on adjacent and distant forests. Bamako, the capital of Mali, is supplied by a zone with a 100-km radius (Simmons, 1989), but most of the 612 tons per day arriving in Delhi, India comes from 700 km away in Madya Pradesh (Hardoy *et al*., 1992), and charcoal from northern Thailand is exported to Bangladesh (Tolba *et al*., 1992). Locally, firewood removal can be very important. Wood is known to be scarce around Kinshasa in Zaire, Brazzaville in the Congo, Nairobi in Kenya, Niamey in Niger, Ouagadougo in Burkina Faso, and in much of Nepal (Williams, 1990). More than 90% of the energy in some African countries depends on biomass (fuelwood). Even if climate does not change, the combination of population growth and a declining resource in some cases will bring cost pressure to change the fuels for cooking and heating from wood and charcoal to other fuels (see Chapter 11). Because of uncertainties in water-resource projections derived from current climate models, providing reliable regional projections of future moisture conditions in these countries is very difficult, although researchers are working on the problem (e.g., Magadza, 1993). Analysis of this situation should be a top priority for energy planners. Further details are provided in Chapter 11.

Many developing countries and some developed countries depend significantly on hydroelectric power (World Resources Institute, 1992). Even constant per capita electricity consumption implies that without major additions from technical potential, hydropower could decline significantly as a source of power by the early part of the next century. Management of some hydroelectric power systems could be significantly complicated by reduced snowpacks, which change the seasonality of storage and supply, and greater flood intensities if rainfall increases. Geographically extensive hydroelectric systems may be surprisingly unaffected despite climate sensitivity of some components (Sias and Lettenmaier, 1994). Rising electricity consumption and (perhaps) declining future capability resulting from climate change could force some nations to rely increasingly upon fossil fuels. For additional details concerning the effects of climate change on energy supply, see Chapter 11.

12.3.3. Air Pollution, Waste Management, and Sanitation

Climate change does not directly lead to air, water, or soil-column pollution. However, if changes in climate significantly alter local and regional weather patterns, underlying trends in pollution damage may change nonlinearly. This issue received only brief attention in the 1990 and 1992 assessments. Global monitoring of urban air quality in cities indicates that nearly 900 million people are exposed to unhealthy levels of sulfur dioxide (SO_2) and more than 1 billion are exposed to excessive levels of particulates (Schteingart, 1988). While cities such as Manchester, London, Tokyo, and Frankfurt have seen great improvements in air quality (especially SO_2), other cities in the low latitudes have increased SO_2 levels. Moreover, photochemical smog produced by the reaction of sunlight with ozone and photochemical oxidants, such as peroxyacetal nitrate (PAN) from nitrogen oxides (NO_x) and hydrocarbon emissions, is particularly prevalent in cities in semi-arid regions, such as Los Angeles, Tehran, and Mexico City. In British cities, NO_x is probably of more concern now than sulfur oxides (SO_x). Warming can exacerbate the formation of smog. Global warming appears likely to aggravate tropospheric ozone and other air-quality problems in polluted urban areas, which in turn may increase human respiratory disease. In developing countries, much of the pollution problem comes from small and numerous sources rather than large industrial sources (Parikh, 1992).

Rapid industrialization and high urban growth rates have engendered major air-pollution problems in urban centers (e.g., Brazil, Chile, Mexico, Malaysia, Indonesia, Thailand). In Mexico City, for example, severe pollution stems from 36,000 factories and 3 million motor vehicles emitting 5.5 million tons of contaminants per year (Schteingart, 1988), leading in part to high blood levels of lead in newborns (Schteingart, 1989). Box 12-1 describes the complexity of interacting urban growth and air pollution problems of the Basin of Mexico (Mexico City and surrounding urban area). Similar problems are caused by private diesel buses in Santiago, Chile (Crawford, 1992) and by the use of smoky, high-sulfur coal briquettes in domestic stoves in Chongqing, China (Wang *et al*., 1994). In all of these cases, if climate change were to add to the number of air-stagnation periods, the effects on human health and economic productivity (from pollution itself or from emergency countermeasures) would be more severe.

Many landfills, abandoned industrial waste dumps, agricultural chemical residues in soils, and polluted river and lake sediments pose long-term potential chemical "time bombs." A chemical time bomb is defined as a time-delayed, nonlinear response of soils, sediments, and groundwaters to stored pollutants under changing climate and land-use conditions (Hejkstra *et al*., 1993). The metabolism of human settlements is responsible for these potential chemical time bombs—some of which, such as landfills and old industrial sites, lie directly in urban areas. Hydrological modifications, especially if rainfall intensities increase following climate change, could lead to more rapid leaching from old landfills that are not watertight, affecting groundwater tables and thus drinking-water supplies. Land-use modifications driven by changes in water availability or altered economic situations could lead to changes in ground cover that mobilize toxic residues in soils (Hesterberg *et al*., 1992). In forests, an increase in temperature and a reduction in transpiration by trees leads initially to increased mineralization of organic matter, followed by nitrification and mobilization of hazardous substances (Mayer, 1993).

The rapid urbanization of low-lying areas in many developing countries has resulted in poor sanitary conditions and low water quality. In many cases, this degradation is exacerbated by natural climatic phenomena. For example, in the rapidly growing coastal cities of Lagos, Port Harcourt, and Warri in Nigeria, wastewater and sewage are discharged into open wayside gutters. Flooding during the rainy season produces an unhealthy and noxious environment (Udo *et al*., 1990). Since these areas are also subject to sea-level rise and perhaps more intense and extended coastal storms under climate change, the triple effects of urbanization, poverty, and climate change could make the environment in cities like these dangerous for human health.

12.3.4. Infrastructure

Except for a reduction in the degree of expected sea-level rise and more emphasis on extreme events, little has changed in our understanding of this issue since the 1992 assessment concerning direct impacts of climate. However, the indirect impacts of climate and socioeconomic change were not discussed in earlier assessments. Although bridges, roads, and buildings can have a physical lifetime of several hundred years when properly maintained, urban infrastructure often has a rather short lifetime because population, urban activity, and other factors often change significantly within shorter time periods than the physical lifetime of the structure. Such socioeconomic change

Box 12-1. The Challenge of Urban Growth and Air Pollution: Mexico City

The metropolitan area of Mexico City (AMCM) consists of more than 2,000 square kilometers, comprising the Federal District (where the government seat is) and 21 adjacent municipalities in the State of Mexico. Growth of 5% per year from 1940 to 1980 and 2% per year for the last 10 years has resulted in 15 million inhabitants in 1990, making the AMCM one of the largest cities of the world. As the country's political, economic, industrial, and social capital, Mexico City contains about 20% of the national population, provides 47% of all jobs in industry, and generates 48% of public investment in social welfare (Aguilar and Sanchez, 1993). It also contains 30% of all the industrial plants in the country (a total of 38,000), which contribute 20% of Mexico City's pollution, and has about 2.5 million motor vehicles that consume about 14 million liters of gasoline and 4 million liters of diesel fuel per day, generating 75% of the pollution in the city (Departmento del Distrito Federal, 1987).

Mexico City's location in a deep valley at approximately 2,300 meters above sea level creates a natural isolation and contributes to frequent thermal inversions (especially in winter), preventing the dispersion of pollutants. Ecological damage has been aggravated by the lack of measures to protect the local environments. GCMs are silent on the question of local winter temperature inversions, but more frequent or persistent inversions would worsen the Mexico City air quality, while less frequent inversions would improve it.

A comprehensive program of action was announced in 1990 to rationalize urban transport, improve the environmental qualities of fuels burned, install pollution-control equipment, and regenerate natural areas (Mendez, 1991). Some of the main actions taken in this new program also would reduce emissions of greenhouse gases:

- Emission of atmospheric pollutants was controlled in service facilities, such as public baths, dry-cleaning shops, and laundries. These places frequently did not comply with technical standards because of their old equipment and a notorious lack of maintenance.
- Industries in the basin were inspected regularly and systematically to verify the correct functioning of their now-mandatory pollution-monitoring and emission-control equipment.
- Checking vehicular exhaust emissions became mandatory in late 1989. From 1991 onward, the regulation was changed to compulsory verification every six months for heavy-use vehicles and yearly for all other vehicles.
- The use of each car was banned one day of the week, according to the numbers on the license plate, to reduce the circulation of vehicles by approximately 500,000 cars, on average, during working days.
- In 1991, unleaded gasoline and catalytic converters became obligatory in all new cars. However, the lower levels of lead increased the amount of unburned oil residues—which, in turn, increased the ozone formed in the air of the city during daylight hours (Bravo *et al*., 1991).
- The two thermoelectric plants in the basin increased their consumption of natural gas as a substitute for oil.

Despite all these measures, atmospheric pollution has remained dangerous to human health. Public officials acknowledge that employment and productivity in the urban economy is still a priority over environmental preservation (Mumme, 1991). Furthermore, some industrial plants have yet to install antipollution devices. Because of the high cost involved, these plants will depend on state credit programs that are to be implemented in future years to afford these devices.

Additionally, because of the ban on using cars once or twice in a week, some people have bought a second or third car in order to drive on all working days. This has increased the number of the private vehicles by about 20%, as well as the consumption of gasoline. Catalytic converters are optional for used cars, which represent most of the private vehicles in the urban areas. As a result, atmospheric pollution has remained at critical levels in the past five years. Not only have some individual pollutants frequently exceeded what are considered the healthy limits, as is the case with ozone, but the overall air-quality index (abbreviated in Spanish as IMECA) has surpassed 100 points—the air-quality norm recommended by the World Health Organization during most of the year. This fact indicates that at least some pollutants are well above the healthful limit and that long periods of exposure to high pollution levels are notable.

requires renewal or alteration of infrastructure. Adaptation to climatic change becomes an important factor in the design of infrastructures with long lifetimes.

A significant component of the increase in costs associated with risks to infrastructure occurs because the "built environment" has become more valuable over time as investments have occurred. Although some infrastructure has become better designed against natural hazards, risks to infrastructure could increase over time, even without climate change. As with population, human settlement infrastructure has increasingly concentrated in areas vulnerable to flooding, fires, landslides, and other extreme events. Much of the increase in the value of these physical assets has come because of rising per capita wealth (Stavely, 1991; Central Statistical Office, 1994). These assets are often housed in lightly constructed residential property, which in the case of Hurricane Andrew in Florida accounted for 65% of all insured losses (IRC, 1995). Use of modern construction materials (e.g., aluminum sheeting used for roofing) and aesthetic design features without sufficient understanding of their appropriate use has compounded the damages of extreme events. Modern buildings are difficult to repair if structural pillars are damaged (Jakobi, 1993), and exterior and contents damages also can add up to severe losses (FEMA, 1992). Although the amount or proportion of national physical assets exposed to climate hazards is not readily available, it is known that in the United States about $2 trillion in insured property value lies within 30 km of coasts exposed to Atlantic hurricanes (IRC, 1995); in the Netherlands $186 billion lies in the hazard zone. The corresponding total in Japan is $807 billion (WCC, 1993, 1994), and in Australia, $25 billion (uninsured) (Peele, 1988). Elsewhere, the value of exposed assets is not well known, but Hohmeyer and Gartner (1992) updated a 1971 estimate to give $22 trillion. This value may have doubled due to economic growth since the 1970s. Insured values are usually considerably less than total values because of the difficulty and expense of obtaining coverage.

Climate can directly affect infrastructure via atmospheric processes, fire, and flood. Some researchers have found, for example, that return periods for major flood events may increase fourfold by the year 2070 (Gordon *et al*., 1992; Smith, 1993; Whetton *et al*., 1993; Bates *et al*., 1994); that is, the 100-year flood would become the 25-year flood. If so, design and safety standards would have to be revised for culverts, drains, bridges, dikes, and dams. Moreover, existing infrastructure would be more vulnerable to failure (Minnery and Smith, 1994). Lake levels in many regions in the world are known to fluctuate under current climate conditions, in some cases changing more rapidly than settlements can adapt to easily (Dejoux and Iltis, 1992) or influencing water quality (Gafny and Gasith, 1989, 1993). This fluctuation occurs both because of varying precipitation and runoff and because of variations in human withdrawal of water for a variety of purposes. Climate change could add to the list of variables affecting lake levels.

Protection of infrastructure from extreme rainfall events, river flooding, landslides, and coastal flooding could become a more serious problem with climate change, in some cases pointing toward retreat from hazardous areas. As noted in Chapters 9 and 17, many inhabited areas in the world, especially those in coastal zones, are already sensitive to flooding, landslides, and wind damage under existing climate (e.g., see Ojo, 1991). Some coastal areas, most notably river deltas, face relative sea-level rise already due to geological factors; withdrawal of oil, natural gas, and water from geological formations underlying the delta regions; and sediment impoverishment because of water and flood control works. Coastal zone agriculture, coastal mangroves, and coral reefs are important to human settlements in some parts of the world (Morgan, 1993; Yoshino, 1993) and are sensitive to sea-level rise. Based on a population-at-risk concept (populations subject to annual flooding), a 1-meter sea-level rise, and year 2020 populations, Hoozemans *et al*. (1993) note that very large populations are sensitive to sea-level rise in Bangladesh, China, Egypt, India, Mozambique, Pakistan, and Vietnam. Others note particular locations at risk, like Jakarta, Indonesia (Sari, 1994). Excluding Mozambique and Vietnam, projected aggregate annual costs of protection were $290 million for these countries, less than 1% of their gross national product (GNP). Countries with costs of protection above 5% of GNP included Anguilla, Cocos Islands, Gambia, Guinea-Bissau, Guyana, Kiribati, the Maldives, the Marshall Islands, Mozambique, Tokelau, Turks and Caicos, and Tuvalu. Fankhauser (1995) has calculated annualized coastal-protection costs for the world on the order of $1 billion per year for a recent estimate of a 50-cm sea-level rise by the year 2100. Inundation and erosion in OECD countries are about half the world total, accounting for between 0.01 and 0.27% of 1985 GDP in OECD countries (Rijsberman, 1991). More refined analyses have been done of several countries' coastal infrastructure-protection needs, including the Netherlands (UNEP and Government of the Netherlands, 1991) and Japan (Kitajima *et al*., 1993). Optimal protection strategies have been investigated for several locations, including the Netherlands (UNEP and Government of the Netherlands, 1991). See Chapter 9 for additional details concerning coastal impacts and costs.

Settlements in forested regions in many areas are vulnerable to seasonal wildfires. This includes settlements in temperate-zone regions such as Canada (Forestry Canada, 1991), tropical forested regions such as Borneo (*Economist*, 1994), and mediterranean climates like the state of California in the United States or southern Australia (Cheney, 1979; Foster, 1994). If the climate in these areas should become even drier and warmer, the frequency of fire danger would increase (Street, 1989; White, 1992; Ryan, 1993), although it is possible that fuel buildup under drought conditions would decrease, decreasing fire intensities.

Such information needs to be developed for other climate-related impacts. One potential adaptation to a wetter climate or to a warmer climate in an area vulnerable to river flooding from snowmelt would be to expand or reinforce riverine flood-control systems with dikes, check dams, and expanded storage facilities. Alternatively—or in addition to these measures—land-use planning and regulation can be strengthened for hazardous areas. The costs of these actions have not been estimated in relation to climate change, at least in part because the location of future climate-enhanced flood danger is so poorly understood that any estimate would be largely speculation.

Transportation impacts were discussed in the 1990 and 1992 assessments and are discussed in greater detail in Chapters 11 and 21. The findings are locality-specific and have not changed significantly. Although in the colder regions global warming may encourage the poleward expansion of human settlement and open some winter water travel (Sanderson, 1987; Stokoe *et al*., 1987), thawing of the permafrost may also disrupt infrastructure and transport (loss of foundations for airports and runways; loss of seasonal ice roads) and adversely affect the stability of existing buildings and conditions for future construction (IBI Group, 1990). If extreme rainfall events become more common, impacts on roads, railways, and other transportation links could become global in reach. Although cost estimates do not exist, they could be very high.

Human muscle power, draft animals, and small watercraft still play a significant role in transportation in many parts of the developing world, especially in the rural areas of those countries located in tropical and subtropical climates. For example, in India, about 10% of tonnage moves by truck, while bullock carts take more than two-thirds (OTA, 1991). Where more frequent or severe heat stress is a possible result of climate change, the work capacity of both humans and draft animals may decline, making transportation less efficient. Where severe weather is more frequent or intense, small craft on rivers, lakes, and other water bodies may be more subject to reduced periods of operation, disrupting farm-to-market distribution systems.

12.3.5. Water Supply

The conclusions for water supply are not dramatically different from the 1990 and 1992 assessments. For example, although some of the details have changed, infiltration of seawater into coastal aquifers is still considered a general potential hazard of sea-level rise, as discussed in Chapter 9.

Changes in water distribution resulting from changed precipitation patterns are important to agriculture, energy, and health. For example, changes in water quality and availability may affect human settlements indirectly through flooding or drought-induced famine and malnutrition. Despite the drilling of many wells, the great Sahelian drought in West Africa during the period 1968 through 1973 (caused by adverse weather compounded by increased human and livestock population pressure on an area of limited long-term biological productivity) resulted in a significant amount of human migration. The 1972–1973 period brought large numbers of rural people from the Niger Republic, Chad, and the far north of Nigeria into the urban areas of Nigeria, including the southern cities of Lagos, Abeokuta, Benin, Warri, Port Harcourt, and Calabar—compounding the urban problems of those cities (Udo *et al*., 1990). Much of the rapid population growth in the Valley of Mexico has been attributed to a continuous influx of rural residents from drought-ridden agricultural areas (Ezcurra, 1990).

Even under current climate, water availability remains a major and accelerating problem for large human settlements in locations as diverse as California (Vaux, 1991) and Houston, Texas (Scheer, 1986), in the United States; Bombay and Madras in India (Leichenko, 1993); and much of northern urban China (Smil, 1993). Lack of access to clean drinking water is highly correlated with numerous adverse health conditions, including high infant mortality (Parikh, 1992). Water quality can be adversely affected by nonpoint pollution, saltwater intrusion into estuaries, lowered stream flows, and groundwater mining—all problems associated with climate change, human-population growth, economic development, or all of the above (Jacoby, 1989).

Demand for water is affected by price, income, technology, and other influences. Other things being equal, more water is used as temperatures increase. For example, in Japan, urban water demand has been estimated to increase about 3.3% per degree celsius for days when the maximum temperature is over 17°C (Hanaki, 1993). For additional discussion of the effects of climate change on water supplies, see Chapter 14.

12.3.6. Health

The earlier assessments of global climate change in 1990 and 1992 provided little information on the potential effects of climate change on human health. More recent thought reveals several additional causes for concern (see Chapter 18 for details). This section describes the specific role of human settlements. Climate-related changes in human settlements may affect several elements that are critical to human health. Kalkstein (1993) and Kalkstein and Smoyer (1993) suggest that the major potential pathways are heat stress directly causing premature mortality (particularly in nonacclimated, unprotected populations in hotter developing countries); outbreaks of infectious diseases whose ranges change because of changes in human migration patterns and spread by contact or close proximity between infected and noninfected individuals; and effects of infectious diseases whose agents, vectors, hosts, ecological niches, or predators on vectors are affected by climate, or compounded by changes in land use, eutrophication of waters, and other anthropogenic environmental insults, such as acid rain or pesticides. The infectious diseases include several serious tropical diseases. In addition, if water supplies are disrupted as a result of more frequent droughts and floods, the full range of nontropical waterborne diseases such as cholera, typhoid, diarrheal, and helminth diseases (hookworm, roundworm, etc.) spread by unsafe drinking water may come into play more frequently.

Anthropogenically and climatically reduced biodiversity (e.g, from prolonged droughts) is a particular concern because biodiversity provides the prime buffer of ecosystems against stress and provides for the biological control of pests and pathogens. Tropical and waterborne diseases and diseases directly transmitted person-to-person annually account for about a fifth of the total annual world loss of disability-adjusted life years from all causes, including other health conditions, accidents, and war (World Bank, 1993). The disability-adjusted life year is a statistic that combines the loss of years of life to premature death with an index of the lost quality of life produced by varying degrees of persisting disability (e.g., blindness or paralysis). There are adverse implications for worker productivity, trade, transport, and tourism (Epstein, 1994).

Urban settlements, particularly the often (but not always) overcrowded and poorly serviced slums, shanty towns, and squatter settlements of the developing world, provide a potentially excellent breeding ground for disease organisms and vectors, as well as poor sanitation and vulnerable populations in close proximity to each other (WHO Commission on Health and the Environment, 1991). These settlements are often located in the least desirable areas, which may be flood-prone lowlands, hazardous waste sites, downwind from industrial sites, or on steep hillsides; therefore, inhabitants will be more vulnerable to, and weakened by, waterborne disease, pollution, and natural disasters, such as floods and landslips. As some agents of infectious diseases become increasingly drug-resistant (e.g., tubercle bacilli and malarial plasmodia) and vectors resistant to pesticides, the importing of these infectious diseases to highly concentrated, vulnerable populations becomes a significant public-health concern.

Tropical Chagas' disease, a leading cause of heart disease throughout the Americas, is becoming increasingly urban. Reports from Honduras and Chile reflect this rural–urban shift, paralleling the movement of populations. Once prevalent in the blood supply, Chagas can be spread directly by blood transfusions. A greater number of heat waves could increase the risk of excess mortality. Increased heat stress in summer is likely to increase heat-related deaths and illnesses (Kalkstein and Smoyer, 1993). Deaths due to cold exposure and blizzards in colder regions like Canada could decrease, although these gains are unlikely to offset the increases in heat-related deaths (see Chapter 18).

Global warming appears likely to worsen air-pollution conditions, especially in many heavily populated and polluted urban areas. Climate change-induced alterations in photochemical reaction rates among chemical pollutants in the atmosphere may increase oxidant levels, adversely affecting humans and complicating the effects of increased urbanization in locations like Mexico City (Griffith and Ford, 1993) or Tehran (Bonine, 1993). The range of certain vector-borne diseases, such as malaria, yellow fever, and dengue, may extend both in latitude and altitude to new areas and settlements currently at the margins of endemic areas. For example, highland cities such as Harare and Nairobi, which are currently malaria-free, are vulnerable (see Chapter 18 for a more complete discussion).

Still another mechanism through which global warming might affect human health is through harmful algal blooms, which promote diseases like paralytic, diarrheal, and amnesic shellfish poisoning, as well as cholera (Epstein *et al*., 1993). The increase in blooms worldwide is thought to be a direct consequence of human activities on a local or regional scale that could be reinforced by the existence of environmental conditions such as warmer seawater in coastal areas that promotes growth. Excess nutrients from sewage and fertilizers, over-harvesting of fish and shellfish, and loss of coastal wetlands and coral reefs also contribute to the problem.

12.4. Extreme Events

12.4.1. Types of Events

Climatologically, extreme events are associated with "anomalous" weather, sometimes defined in terms of a "return period" of 10 years, 100 years, or some other value (probabilities equivalent to one event in 10 years, 100 years, etc.). The length of the return period is decided on a case-by-case basis, depending on (1) the climatic phenomenon, such as flood, wind damage, and drought; (2) the climatic region or zone; (3) the season; and (4) the intensity of the impact on human activities, plants, and animals. Extreme amounts/values that cause damage change from year to year as the level of human development and activity in the area changes. Therefore, it is very difficult to define threshold levels of temperature or precipitation that can be used as permanent criteria in any one region or applied everywhere in the world.

One important aspect of extreme events is the apparent randomness and abruptness with which they arrive. Gradual changes in air pollution, acid deposition, desertification, water shortages, salt water intrusion, soil degradation, and deforestation are also serious but tend to arrive slowly enough that local/regional/national authorities can take successful long-term countermeasures.

Extreme events may arrive without any definite cycle or periodicity, so they constitute risks that can be the subject of insurance. For the effects of climate-related extreme events on insurance and the insurance industry, see Chapter 17. Extreme events are often related to disease outbreaks. El Niño/Southern Oscillation events and teleconnected weather patterns across the globe (Glantz *et al*., 1991) are highly correlated with outbreaks of malaria (Bouma *et al*., 1994), dengue, and algal blooms (Hallegraeff, 1994), as well as other problems (Glantz *et al*., 1987). Both droughts and floods are related to outbreaks of vector-borne diseases and agricultural pests. The number of extreme events in terms of economic and insured losses is increasing, at least in part because of the ever-increasing scale of human activity. The amount of insured losses caused by extreme events is increasing at a higher rate than is the amount of economic loss. Insured losses at the beginning of the 1990s are two to three times those of the 1980s (Berz, 1993a, 1993b).

12.4.2. Mechanisms of Effects

To discuss the mechanism of effects of extreme events on human settlements, we refer to the example of typhoon hits in Japan (Fukuma, 1993). Based on the record for the 79 years from 1913 to 1991, 245 typhoons were classified into six grades based on intensity. Changes in the number of deaths are shown in Figure 12-2, with running 20-year averages since 1921. It is clear that the number of deaths is larger for the more severe typhoons and that deaths have been declining in all categories since World War II. This decline is thought to have occurred because increasingly effective countermeasures have been taken during the last 40 years, including more robust infrastructure design standards. These countermeasures appear to be more effective with respect to the mid-class Grade III typhoons than for either the weaker typhoons (where the lower limit of fatalities may have been reached) or the stronger typhoons (where more effective actions still could be taken).

The countermeasures include conservation of mountain slopes, rivers, and coasts; harmonization of institutions and laws related to disaster mitigation; preparation of systems for disaster prevention, including better design; meteorological observation and information systems; promoting people's consciousness of preventing disasters; and development of communication systems for disaster occurrences. Thus, the impact of extreme events on human settlements can be affected by the grade of the extreme event, the level of economic and technological development, and the extent of countermeasures taken. Climate change may affect the intensity or the probability of extreme events. The impacts on human settlements depend in part on the present vulnerability (including coping ability) of the settlements.

12.4.2.1. Floods

Vulnerable regions are some small islands, notably coral atolls; regions hit by tropical cyclones, such as typhoons and monsoons; and the lower reaches of big rivers like the Mississippi, Hwang Ho (Yellow River), Yangtze, and Nile. Delta regions in South and Southeast Asia are particularly vulnerable. Local-scale floods show various effects on rice yield, as shown by Yoshino (1993) for tropical Asia. Flooding is a common extreme event that poses challenges for the insurance industry and the public sector (in planning and protecting infrastructure). Although humans possess considerable adaptive management capability to deal with floods, flooding could become a more common problem with climate change, even if average precipitation decreases (see Section 12.3.4; Chapters 14 and 17; and Chapter 6, *Climate Models–Projections of Future Climates*, of the IPCC Working Group I volume).

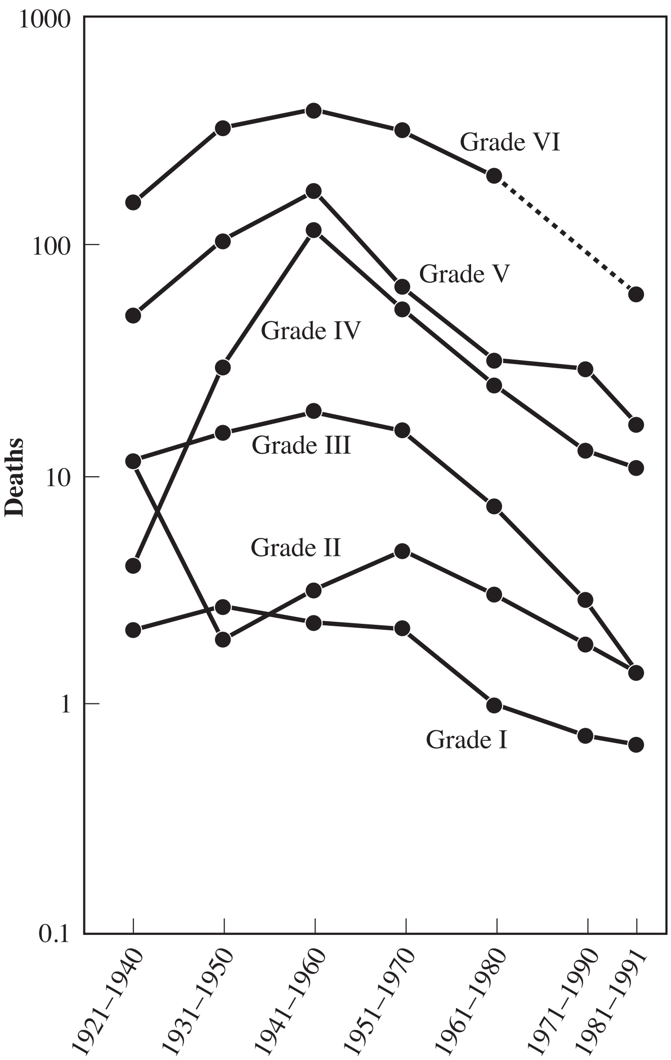

Figure 12-2: Change in numbers of deaths per typhoon hit in Japan during the last 70 years according to Grade I (weak), II (normal), III (strong), IV (stronger), V (violent), and VI (super violent) (Fukuma, 1993).

12.4.2.2. Landslides

Although landslides occur in many regions throughout the world, damaging property and disrupting transportation links, the 1990 and 1992 assessments gave relatively little attention to land stability as a climate-related problem. However, in the poorest hilly cities of the world, many hundreds of thousands of people live in illegal settlements on potentially unstable hillsides especially vulnerable to climate change. Hundreds of people were killed or seriously injured and thousands made homeless by landslides in Rio de Janiero in 1987 and 1992; Medellin, Columbia in 1988; Mexico City in 1990–1992 (Aguilar and Sanchez, 1993); Caracas in 1989 (Hardoy *et al*., 1992); and Hong Kong in 1925, 1964, 1966, 1972, and 1976 (Styles and Hansen, 1989). A similar degree of susceptibility to landslipping would be found in other areas of deeply weathered rock in tropical and subtropical areas subject to heavy rain.

Many landslides are related to inherently unstable materials that move when subject to extreme rainfalls, such as the Loess Plateau of China (Billard *et al*., 1992; Derbyshire and Wang, 1994), the quick clays of Quebec, and the deeply weathered crystalline rocks of the tropics and subtropics (Brand, 1989). Others occur in steeplands, such as the Himalayas, the Alps, and the mountains of western Canada and western China, and may be influenced by earthquakes, rapid snowmelt, or extreme precipitation (Brabb, 1991; Haigh, 1994). Relict periglacial landslides occur in much of Northern Europe and North America (Johnson and Vaughan, 1989). Stable under present natural conditions, these landslides are reactivated by urban construction activities and are triggered by heavy rains (Caine, 1980).

Landsliding is regarded as a catastrophic event—one that is large, sudden, and rare on human timescales (Jacobson *et al*., 1989). Their triggering depends on an earthquake or a rainfall event and is related to antecedent conditions. Alteration in the frequency and magnitude of precipitation related to climate change (caused by changes in tracks of tropical cyclones, for example, or increases in the intensity of rainfall) could alter the probability of landslides and debris flows (Gordon *et al*., 1992). In some places, currently inactive slides may be reactivated; in others the risks of slipping may be reduced. Greater aridity, on the other hand, could so reduce vegetation or so increase the risk of fire (which reduces vegetation) that mud flows and debris flows could become more frequent. In some temperate-zone regions, for example, landsliding in inland areas is likely to become more pronounced as a result of higher winter rainfall, increased likelihood of summer droughts, and increased summer storm activity (Jones, 1993).

Landslide susceptibility also is being altered by the movement of more people into urban areas in mountain environments and the expansion of cities from plains into the surrounding hills, both for reasons of prestige among the rich and lack of affordable building space for the poor. Both the wealthy and poor thus become potential victims.

12.4.2.3. Wind

Vulnerable regions include areas susceptible to tropical and non-tropical cyclones, including west-facing mountainous areas for polar cyclones and upper Westerlies. Strong gusts can also be associated with the downbursts of tornadoes. The countries most affected by tornadoes are the United States, Canada, and Russia, where local areas can experience serious tornado and hail damage (Phillips, 1990; Paul, 1994), though they occur in many parts of the world (Grazulis, 1991). Tropical cyclones (hurricanes and typhoons) commonly affect South, Southeast, and East Asia and Oceania, as well as Central America, the Caribbean, and parts of Mexico and the United States. Some authors suggest that storm tracks may change, or that severe tropical cyclones may become more severe with climate change (Okamoto, 1991). However, there is little agreement among climate models on either mid-latitude storms or tropical cyclones (see Chapter 6, *Climate Models–Projection of Future Climates*, of the IPCC Working Group I volume; also see Chapter 17 for further details on cyclone damage).

12.4.2.4. Heat Waves

Heat waves may become more common and severe if the climate warms. Climatologically, in the Northern Hemisphere, the southern part of the temperate zone and northern part of the subtropical zone in summer are the most vulnerable. In the Southern Hemisphere, sub-Saharan Africa and Australia are both vulnerable, especially when heat is combined with drought. Aerologically, vulnerable areas are the eastern parts of prolonged, stationary upper troughs, where warm air flow from the tropics can invade the temperate zone. Heat waves appear to increase overall death rates, even in acclimatized populations. They are a particular concern when combined with heat islands and substandard housing in urban areas (see Chapter 18).

12.4.2.5. Cold Waves

Similarly, cold waves may become less common or severe. Climatologically, in the Northern Hemisphere, the northern part of the subtropical zone and the southern part of the temperate zone in winter are the most vulnerable. Episodes of extreme cold and blizzards are major climate concerns for the circumpolar countries like Russia and Canada (e.g., Hage, 1985; Phillips, 1993; RSC/CAE, 1994). In the Southern Hemisphere, Antarctic storms sometimes strongly affect weather on New Zealand's South Island. In both hemispheres, severe snow or ice storms can adversely affect most economic sectors. Aerologically, the western parts of the stationary upper trough, where the cold air can more easily flow from higher latitudes, are the most vulnerable areas. In Asia, for example, cold waves can penetrate to 15° to 20°N latitude (Yoshino, 1989; Yoshino and Kawamura, 1989).

12.4.2.6. Droughts

There are meteorological, hydrological, and agricultural droughts. They occur widely, from the tropics to the high latitudes. In the lower latitudes, they are intensified by prolonged dry seasons caused by anomalous monsoon circulation. In the middle latitudes, anomalies in cyclonic activity are effective. The most vulnerable areas are those under the influence of subtropical anticyclones. Droughts could be more severe at higher temperatures because evapotranspiration would be enhanced, reducing soil moisture. Agricultural settlements in regions such as sub-Saharan Africa, Australia, China, southern Europe, and midcontinental North America are projected to be sensitive to drought conditions. See Chapter 13 for details on agricultural effects. Chapter 14 notes that water distribution systems, power plant cooling, and river navigation can be adversely affected and that settlements in the Middle East and North Africa may be particularly vulnerable to drought.

12.4.2.7. Wildfires

So-called "Mediterranean-Climate" regions are at the most risk because of their dry summer climate. The risk of fires is very high in the summer months (Donguedroit, 1991), when severe storms may also spawn lightning strikes. These may become more common if climate changes (Price and Rind, 1993). The regions surrounding the Mediterranean Sea, California in the United States, and southeastern Australia all have suffered from severe fire damage recently. Fires are also frequent in the taiga regions of Siberia, Canada, and Alaska and in Borneo and Indonesia (during El Niño years). These tendencies are related to recent increases in resident population and tourism, inappropriate urban plans and environmental management, shortages of labor in the timber industry, wasteful logging practices and swidden agriculture, lags in upgrading fire prevention systems, and so forth. They could be exacerbated by global warming if it also results in drying or intensification of El Niño conditions and if fuel is available.

12.4.2.8. High Tides, Storm Surges, and Tsunamis

Global warming results in sea-level rise, so the effects of "normal" extreme events such as high tides, storm surges, and seismic sea waves (tsunamis or "tidal waves") would become more severe. Multiple risks such as earthquake and tsunami or storm surge at high tide are of particular concern.

12.4.2.9. Acute Air-Pollution Episodes

In addition to areas historically famous for air pollution—such as London, Los Angeles, and Mexico City—many developing-world cities are becoming increasingly affected. Air-pollution episodes could become more serious if temperature inversions become more frequent or persistent in these areas.

The effects of extreme events are inherently uncertain and carry with them an element of probability or risk. These risks can and have been calculated for anticipated climate change in some regions, such as coastal Japan (Mimura *et al*., 1993). More generally, however, many of today's standard engineering and insurance calculations, which depend on historical observation, could be overturned by changes in the intensity or frequency of extreme events that increase the costs, risks, or both costs and risks to lives, infrastructure, and insurance pools.

Extreme events sometimes occur successively or simultaneously. When this happens, as in the case of a series of typhoon hits, the damage is more serious because the area has been made vulnerable by previous damage (e.g., the ground is already waterlogged, or flood-control structures have been weakened). Sometimes a meteorological extreme event occurs immediately following some other form of disaster, more than simply adding to the stress on social and economic conditions. For example, a severe typhoon struck the Philippines just after the eruption of Mt. Pinatubo, causing severe mudflows at the base of the mountain. Such secondary impacts can be relatively serious in comparison with the damage of the original event.

12.5. Adaptation Options

The list of adaptive actions discussed in this section is adapted from United Nations Centre for Human Settlements (Habitat, 1992b). The list includes both actions autonomously taken by humans and deliberate, planned, climate-adjustment actions nurtured by policy. Where data are available, the section also discusses the costs of adaptation. However, not enough focused research has been done on adaptation to permit full comparisons between adaptation and mitigation of climate change or even to fully characterize the costs of adaptation. Although regional and local governments may have limited powers or boundaries that do not correspond to natural physical systems affected by climate change, a holistic approach needs to be taken to planning human settlements. Each settlement must fulfill multiple objectives, of which adaptation to climate will be only one (and in many cases, not even a very important one). Examples of this holistic approach may be found in Douglas (1983) or White (1994). Sector-by-sector adaptations are discussed in Sections 12.5.1 through 12.5.6.

12.5.1. Population Migration

One of the potentially destructive effects from a variety of social and economic perspectives is forced internal or international population movement—both low-key, long-term migrants responding to relative economic opportunity by moving between regions and from rural areas to cities, and "ecological refugees" responding to specific natural disasters. Economic migration can be reduced if economic opportunity and services of civilization can be delivered to the regions of origin and thus prevent the population movement (Calva Tellez, 1992; Rello, 1993). This reduction can be accomplished in part by immigration/emigration policies if regional (especially rural) and national economic development are undertaken at the same time. Controlling the degree of urbanization appears to be doubtful as a solution (Shukla and Parikh, 1992). Decentralizing government administration to secondary cities reduces to some degree the impact of population movements on primary cities because the "pull" effect of government employment is distributed among several locations. Economic dislocation programs, such as disaster assistance, can offset some of the more serious negative consequences of climate change and reduce the number of ecological refugees. Effective land-use regulation can help direct population shifts away from vulnerable locations such as floodplains, steep hillsides, and low-lying coastlines.

12.5.2. Energy

A number of specific actions can be taken to offset the effects of climate change in the energy sector. Increased building-shell efficiency and changes to building design that reduce air-conditioning load show promise (Scott *et al*., 1994). Though effective, however, some strategies may have other costs (Loveland and Brown, 1990). Air conditioning may offset some of the more deleterious effects of heat waves, although because acclimatization is reduced, this is not necessarily so (McMichael, 1993). Reducing the size of space-heating capacity in response to warmer climate would be a logical adaptive response in more temperate and polar countries and may free up investment funds for other purposes, even within the energy sector. Community design to reduce heat islands (through judicious use of vegetation and light-colored surfaces) (Akbari *et al*., 1992), reducing motor transportation, and taking advantage of solar resources also should be included in the package of possibilities. Many of these actions, such as urban tree planting and urban mass transit, are typically justified as mitigation options to reduce fossil-fuel use in the urban buildings sector (see Chapter 22) or to reduce the adverse energy-use, congestion, and health consequences of transportation networks that are based on automobiles and motorized two-wheelers (see Chapter 21). Full environmental and health costing of fossil fuels, which can discourage the use of fossil fuels through environmental "adders" (theoretical surcharges on the energy produced with fossil fuels for planning purposes to compare environmental consequences or actual surcharges charged to consumers to discourage their consumption of energy produced with fossil fuels), is sometimes regarded as a mitigative action. However, these same mitigative responses also have adaptive value in that they reduce the impact of warming on urban discomfort caused by heat-island effects.

Some of these actions have unexpected social costs if not planned appropriately. For example, urban trees can be aesthetically attractive while reducing air-pollution and heat-island effects, altering local meteorological conditions, and providing shelter from wind (NCPI, 1992). However, they also can accelerate desiccation of clay soils (Freeman, 1992)—leading to subsidence—and contribute windthrow to property damage during high-wind events (Stavely, 1991; Shearn, 1994). See Chapter 17 for further details.

Until recently, traditional styles of clothing, buildings, and cultural features such as hours of work varied considerably around the world, mirroring the outdoor environment and each region's unique sociocultural and technical response to it (Shove, 1994). Unique cultural response has been overtaken by standardization in hours of work, clothing, and heating and cooling technology, including standardized definitions of human comfort and "ideal" indoor environments (Fanger, 1970; King, 1990; Baker, 1993). Localized culture- and situation-specific responses, such as reintroducing the "siesta" or varying the strategy between the prestige commercial sector (hotels, banks, and offices) and the residential sector, offer the opportunity to have a less energy-intensive response to global warming. Locally specific strategies will reflect the distribution of wealth and status, slowing if not reversing the trend to globalized lifestyle and standardized indoor environment.

12.5.3. Air Pollution, Waste Management, and Sanitation

Reducing industrial pollution is a desirable activity under current climate because it can not only reduce acute health-threatening conditions like heat waves but also can reduce other pollution-related problems, such as the buildup of heavy metals in the environment, loss of aquatic biodiversity, and loss of forested areas. Reductions in the burning of fossil fuels not only have an impact in solving all of the foregoing problems but have mitigative effects on global warming itself. Reducing automotive traffic in sensitive airsheds has a similar effect, as does substitution of more benign fuel types (e.g., natural gas for coal and the use of unleaded gasoline).

Countermeasures for chemical time bombs include a complete inventory and system of monitoring for urban-area landfills and waste sites; tight control of waste flows from source to final resting place for present waste disposal; and dumping of toxic materials only in safe, permitted sites. Such control is difficult to maintain in poor cities that lack adequate urban infrastructure but is extremely important because so many people depend on shallow groundwater wells. In rural areas, control is more difficult, especially for widely used agricultural chemicals. Safe disposal of containers and residual amounts is extremely important but often neglected, particularly where the chemicals are used by laborers for absentee landlords on large estates.

Although increasing human activity and urbanization are likelier to have more important impacts on sewage management than will climate change, the impact of climate change or the necessity of reduction in GHGs may influence sewage-management policy in the direction of water recycling and reducing energy use. Water demand will increase in many urban areas, whereas severe reduction in available potable-water resources because of climate change is predicted in some areas. By necessity, reuse of treated sewage will increase to cope with relative shortage of urban water resources. Limited reuse of sewage has been applied in areas that are subject to dry climate (South Africa, Israel, California, etc.) or in areas with very high density of urban activity (e.g., Japan). These examples show that reuse of treated sewage for flush toilets, industrial use, agricultural use, or even part of the raw water destined for potable water supply is technologically possible. For some uses, waterborne toxins not addressed by conventional treatment can be a concern.

The reuse of treated sewage requires advanced sewage-treatment technology in addition to the more-conventional secondary treatment. There are many options in the advanced treatment category. Depending on the proposed quality of treated water, its cost and consumption of energy and resources vary. Some of the advanced treatments consume much more energy than the conventional sewage treatment processes. Energy-intensive processes often tend to be adopted in the developed countries so that the quality of treated water obtains acceptance from the public. Savings in energy consumption are important and should be taken into account in such cases. On the other hand, inexpensive and less energy-intensive methods are normally chosen in the developing countries. Such a choice is desirable from the view point of the global environment, but high priority should also be given to avoiding hygienic risk either by using a high grade of treatment or by limiting the uses of the treated sewage.

12.5.4. Infrastructure

As described in the 1992 assessment with respect to the coastal zone in particular, available adaptive responses to flooding fall broadly into three categories: retreat, accommodation, and protection. There are various environmental, economic, social, cultural, legal, institutional, and technological implications for each of these options. Retreat could lead to a loss of property, potentially costly resettlement of populations, and, in some notable cases, refugee problems. Accommodation could result in declining property values and in costs for modifying infrastructure. Protection may require significant investment, can have environmental costs to shorelines, and may be ineffective if the frequency or magnitude of extreme events increases. Generally speaking, building codes and other design and construction standards offer one of the most effective ways to limit the effects of extreme events such as tropical cyclones and flooding. As the climate changes, the standards need to be periodically revisited and updated. The supporting analysis for the standards needs to be couched in the language of engineers so that design solutions reflect increased climate uncertainty and risk of natural hazards. Also, developing countries may require assistance in obtaining the necessary knowledge and institutional capacity to develop and implement the standards.

In developed countries, the costs of defending infrastructure from river and coastal flooding have been calculated for numerous sites, but mostly for extreme events under current climate conditions. There have been a growing number of region- and city-specific studies that suggest that climate change could prove costly to major urban areas in coastal zones of developed nations. Examples from the United States (Walker *et al*., 1989) and Japan (Mimura *et al*., 1993; see Figure 12-3, which shows typhoon-vulnerable areas of the Tokyo metropolitan area) illustrate the point.

In Japan, protection of coastal infrastructure was estimated to cost $63 billion for raising port facilities (quays, wharfs, jetties, seawalls, etc.), plus $29 billion for coastal facilities (water gates, breakwaters, seawalls, etc.) (Mimura *et al*., 1993). For an extended discussion of strategies and further international estimates of the vulnerabilities and costs of sea-level rise, see Chapter 9, Hoozemans *et al*. (1993), or IPCC CZMS (1992); also see Chapter 17.

Although no comprehensive international estimates have been made of additional pumping-station, water-supply, or drainage requirements for coastal regions, some analyses have been done of the requirements to maintain water balances in some areas. For example, Arai (1990) analyzed the water balance in Tokyo. A handful of estimates have been done on the costs of adapting to changes in lake levels, in the range of a few hundred million dollars for small areas in Lake Michigan (Changdon *et al*., 1989) and Lake Titicaca.

Identification and mapping of landslides provides information on what has happened in the past, but such landslide inventory maps at a scale of 1:100,000 or larger probably cover less than 1% of the land and sea areas of the world. Several urban areas with particular landslide problems have set up detailed schemes for landslide mapping and landslide risk assessment. The work of the Geotechnical Control Office in Hong Kong (Brand, 1989), the San Mateo County Gas Project in California (Brabb, 1993), and the Colorado Geologic Survey (Mears, 1977) are good examples of such schemes. However, many of the poorer countries of the tropics have little information. Even in developed countries like Britain, a detailed inventory of landslides was not completed in the 1980s (D.K.C. Jones, 1991). From such inventories, landslide susceptibility maps can be produced.

Landsliding is usually predictable, and a wide range of techniques is available to help urban planners minimize risk through avoidance, control, and improved resistance (Jones, 1993). Landslide susceptibility maps show areas with different potentials for future landslide movement. Real-time warning systems for landslides are rare, but successful operation of a debris-flow warning system for the San Francisco Bay region indicated that, where sufficient telemetric rain gauges are available, adequate warning may be achieved. Many countries, however, rely on structural measures to mitigate debris flows and rock avalanches. In western China, for example, many long training walls restrict the width of debris flows down valley floors. The safety of such measures could require reevaluation. The effectiveness of a good landslide risk inventory is well illustrated in Hong Kong, where urban land-capability assessment and control of building construction are based on assessments of slope stability (Styles and Hansen, 1989).

Building controls do little for structures that existed before the controls were implemented and those that are built illegally. These situations call for a great increase in understanding and awareness, even in wealthy communities. Many of the poor of the world will continue to exist on hazardous hillsides. Forced evacuation and rigid enforcement of zoning regulations may be only temporary measures unless viable, practical, and economic alternatives are provided for the poor.

Increased storminess or rainfall intensity in regions where settlements are expanding onto hillsides featuring relict periglacial landslides will lead to greater frequency of landsliding. Here, more rigid application of geomorphological knowledge in planning decisions is required. Existing structures that are threatened need to be identified. Particular attention in all regions needs to be paid to mining waste, quarry tailings, and other landfills and spoil heaps, which may become unstable and threaten schools, hospitals, dwellings, business premises, and water quality.

Though the extent of adaptive capacity varies among nations and localities, human beings have developed multiple adaptive responses over the centuries to cope with high fire-danger regimes. Major adaptive responses include both fire prevention and fire control and suppression; use of fireproof and fire-retardant materials such as concrete and steel, rather than wood in buildings; development of extensive firefighting networks in settled areas (including personnel and mechanical firefighting equipment such as fire trucks, fire-hydrant systems, and sprinkler systems in buildings); fire-control systems in rural areas, such as controlled burns to limit fuel, fire breaks, aerial fire retardant delivery, and rural fire departments and "smoke jumpers"; and short-term activity controls during high fire-danger weather, such as prohibitions on open burning, commercial activities such as logging, and recreation activities such as hiking, hunting, or use of off-road vehicles. If frequency or intensity of fire danger warrant, another potential adaptive response involves improved spatial planning of communities and some longer-term land-use controls. These provide better isolation of fires and could limit damage to human settlements. If global climate change makes high fire danger a more common or dangerous occurrence in places such as western North America and southeastern Australia, more frequent and intense application of these principles may reduce vulnerabilities to fire. In locations where fire danger is lessened, relaxation of some controls may be possible and desirable.

Integrating transportation and land-use planning can reduce the demand for transportation infrastructure. While largely undertaken for mitigative reasons, integrating transportation and land-use planning could reduce the adverse impacts of air pollution under current climate as well as reduce urban heat islands and assure that future heat waves would be less of a

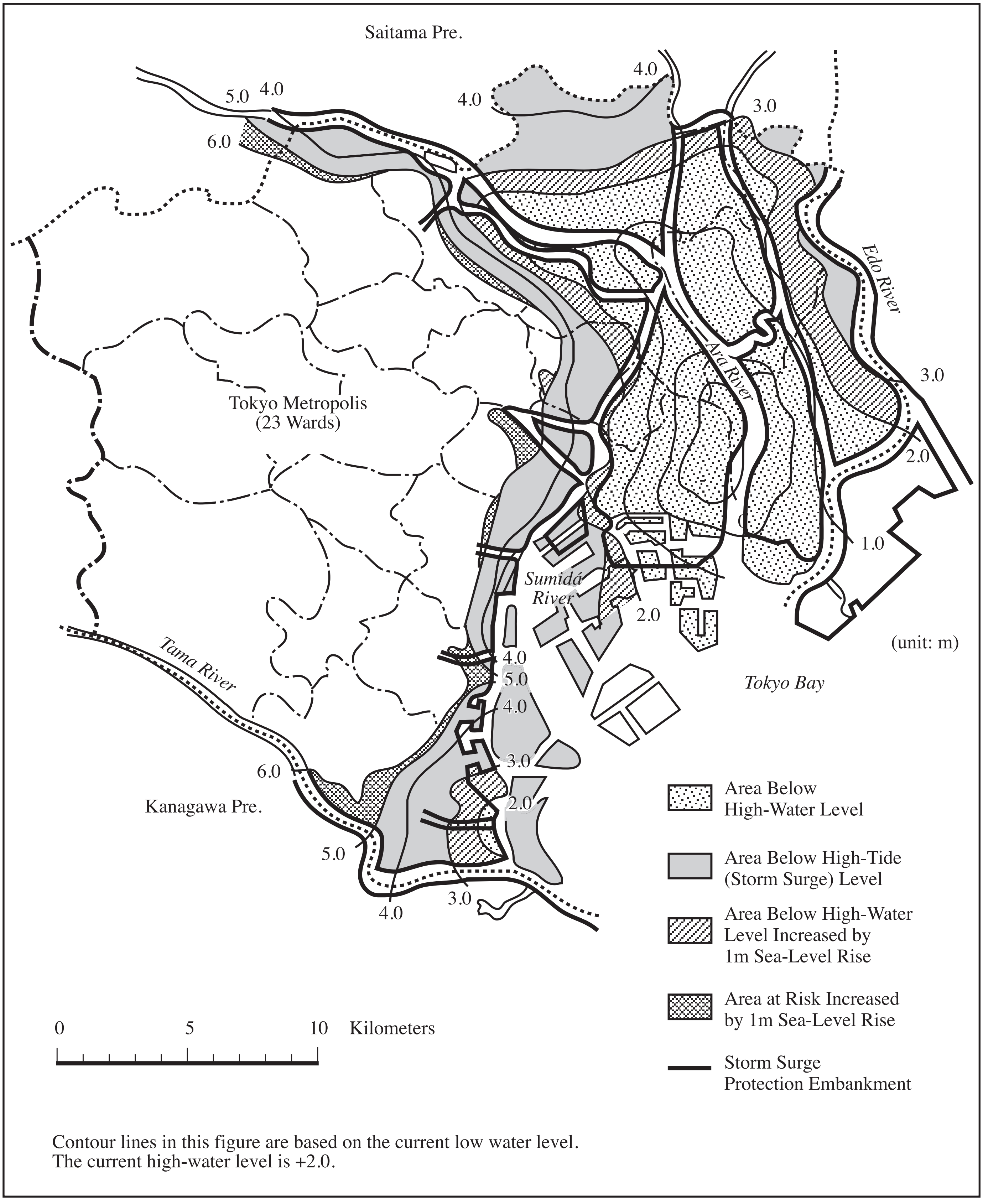

Figure 12-3: Distribution of lowlands and positions of high-tide embankments in Tokyo (Mimura *et al*., 1993).

health and cooling-energy problem than they otherwise would be. Appropriately timed investments—especially public transit and transportation-management schemes—can improve traffic flow, reduce the need for travel, and emphasize appropriate modal choice (especially foot traffic and bicycles for short trips). These appear particularly promising in reducing local urban air pollution in the developing world (OTA, 1991). In addition, adjusting human settlement patterns may strongly affect transportation in the long run (see Chapter 21).

12.5.5. Water Supply

Potential changes in hydrologic balance because of climate change will have an impact on the availability of water resources and eventually on water balance and water supply. However, more significant and acute imbalance between water demand and the water resource is expected in many regions because of the increase both in population and in per capita water demand. Water-shortage problems exist and are becoming increasingly serious even under present circumstances (Laburn, 1993). Severe imbalances are foreseen, especially in developing countries where water demand is increasing rapidly and the institutional system and water supply facilities are still insufficient. Future management must take into account such socioeconomic-driven increases in water demand and the potential decrease in available water resources. Solutions to such imbalances include minimizing net water use and developing new water resources, including limited wastewater reuse. Prevention of water pollution is necessary to maintain a water quality satisfactory enough for potable water supply. See Chapter 14 for additional details on water-management options. The Nordic Freshwater Initiative proposed two key principles for future sustainable development and water use in developing countries (Jønch-Clausen, 1993). The first principle is management at the lowest appropriate levels. Centralized and top-down approaches to water-resource development and management are often insufficient for efficient local management, although the centralized mechanism is good to ensure national economic and social interests. The second principle is to consider water as an economic good. Numerous opportunities exist for improved management of water infrastructure, pricing policies, and demand-side management of supply (Frederick and Gleick, 1989). The cost includes direct cost, opportunity cost, and environmental cost. Charging for water use induces conservation and protection of water resources and develops the consciousness of water management.

12.5.6. Health

A range of adaptive mechanisms for offsetting the potential human-health effects of global warming lie in improving certain aspects of health services and other public services that settlements provide in any case (World Bank, 1993). Improved sanitation and water treatment both reduce the spread of waterborne diseases and may provide a measure of safeguard against importing exotic enteric waterborne diseases such as cholera. Effective inoculation programs against tropical diseases are limited to a few arbovirus infections, principally yellow fever and Japanese encephalitis. Vaccination against cholera is about 50% effective for a period of a few months (American Public Health Association,1990). Improved disease-treatment intervention has reduced mortality and morbidity rates from a number of diseases and could prove an effective, if expensive, alternative in some cases. This strategy could take the form of health and relief services' emergency response to specific disease outbreaks, for example. Improved air-pollution control is desirable from a number of perspectives under current climate and could have beneficial effects on reducing the impact of climate warming. Pest suppression/management can in some instances reduce the prevalence of disease vectors or hosts (e.g., the early twentieth century campaign against mosquitos in Panama) and thus offset to some degree the expansion of range of some of these pests.

Finally, disease surveillance could be strengthened and integrated with other environmental monitoring to design early warning systems; develop early, environmentally sound public health interventions; and develop anticipatory societal policies to reduce the risk of outbreaks and subsequent spread of epidemics. For additional details on health considerations, see Chapter 18.

12.6. Needs for Future Research

We are still very much at the infancy of this topic. Information needed to calculate the effects of climate change on human settlements would answer two broad questions, both of which must be answered at the regional and local level: (1) What is the present situation with respect to human population and settlement infrastructure? (2) What are the options for future economic and social development (especially adaptation to climate), and what will determine which option(s) will be adopted?

- **Present Situation**
  - Generally speaking, consistent, useful estimates of infrastructure types and values, especially in flood zones, do not really exist. Databases on regional capital stock are necessary to calculate infrastructure at risk from extreme events. Information is also required on capital turnover rates to determine "natural" replacement rates.
  - Better-founded information is needed to support estimates of the effects of climate on national energy demand, particularly the balance between heating and cooling in temperate-zone countries, which is currently a matter of some controversy. More needs to be done on the inventories and market penetrations of energy-using equipment in the commercial sector in all countries and in the residential sector of developing countries.
- **Future Situation**
  - We need better information on the probability, location, intensity, and consequences of future extreme climate events of all types. Currently, the

information available from climate models on extremes of temperature, precipitation, and windspeed is inadequate to do more than identify this as an issue.

– Cost estimates are needed for nearly every infrastructure and settlement issue. With the exception of the costs of coastal defense and some studies on energy demand, little has been done on the costs associated with the effects of climate change on human settlements. There are only limited databases on the costs of potential urban flooding and landslides, the costs of migration for infrastructure development, and the costs of health intervention programs and air- and water-pollution prevention.
– Data are needed on technology dynamics. Beyond general principles, we know very little about which variables govern the development and adoption of new technologies. Yet this may have a profound impact on the future shape of human settlements.
– We have better data and theories on population fertility, survival, and death, but regional migration is much more difficult to forecast quantitatively.
– Analysis of the future location of economic activity needs a better theory and better data. The general principles underlying locational choice of industry are known. However, it is nearly impossible to extend these principles beyond particular current business decisions to whole industries, especially for many years in the future. Data are needed on the costs of production, potential suppliers and markets, and the costs of transportation, especially in the developing countries.

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